Wind Error Modeling - Impact on CD&R

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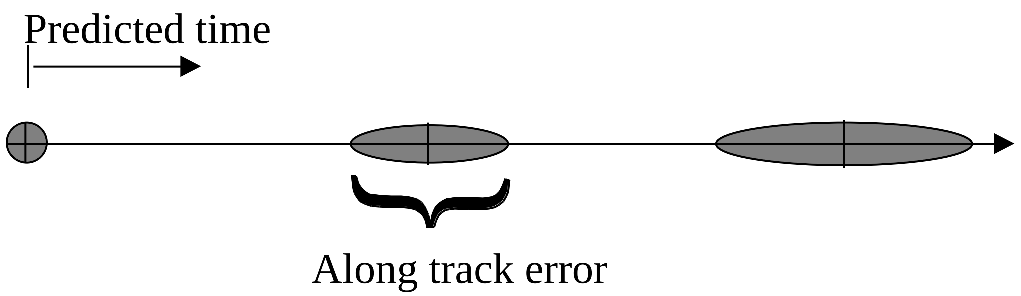
Trajectory Prediction Uncertainty

- Sources of uncertainty (from NASA TP-1998-208439)
  – Aircraft state estimation
  – Trajectory modeling errors (performance, procedures, atmospherics)
  – Clearance conformance
- "The first and most significant error source is atmospheric prediction which has a complex effect on trajectory prediction accuracy"
- Use of airborne conflict tools reduce effect of tracking error
- This presentation will focus on wind uncertainty

Models of Propagation of Uncertainty

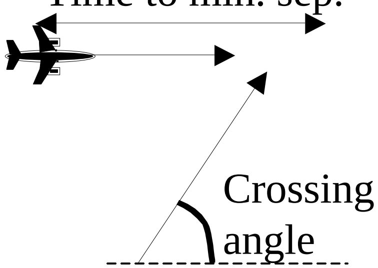
- Linearly growing along-track positional uncertainty applied in the literature

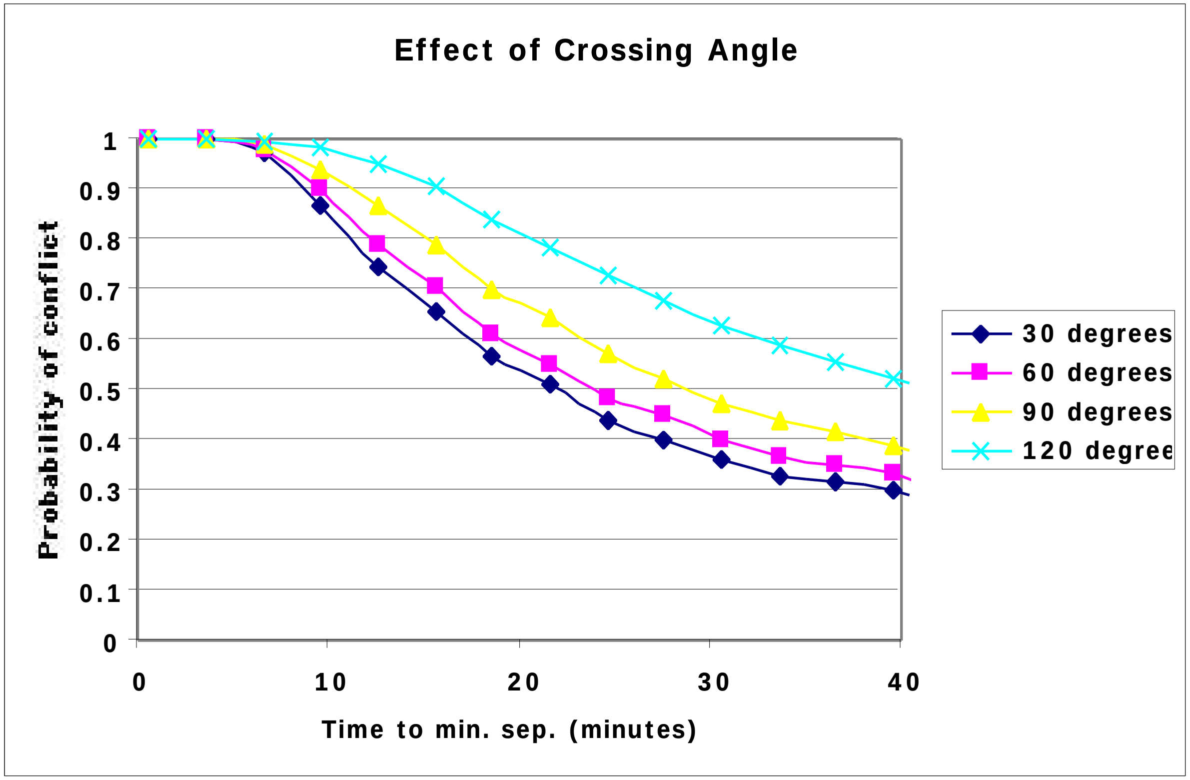


- E.g., Paielli, Russell, A., Erzberger, Heinz, “Conflict Probability Estimation for Free Flight”, J. of Guidance, Control and Dynamics vol. 20 No. 3, May-June 1997, pp. 588-596
- Modeled as a Gaussian with linearly growing rms value (0.25 nmi/ min)
- Cross-track error modeled as zero norm Gaussian with an rms 0.5 to 1 nmi
- Some model the above as a bias error in along-track speed

Effect on Conflict Probability

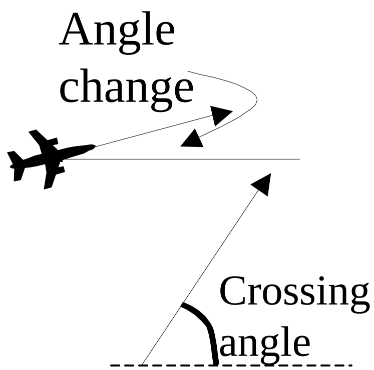
- Monte-Carlo simulation can duplicate results for a crossing conflict

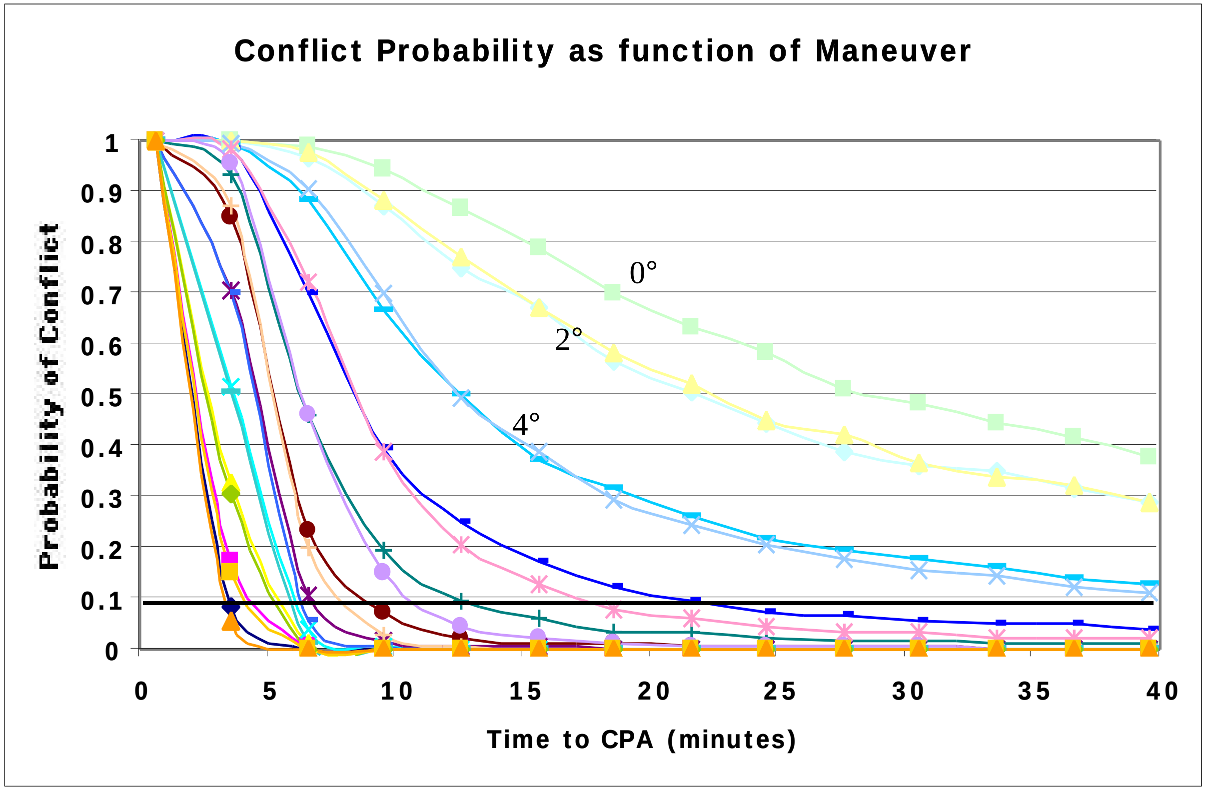




Maneuvers affect probability

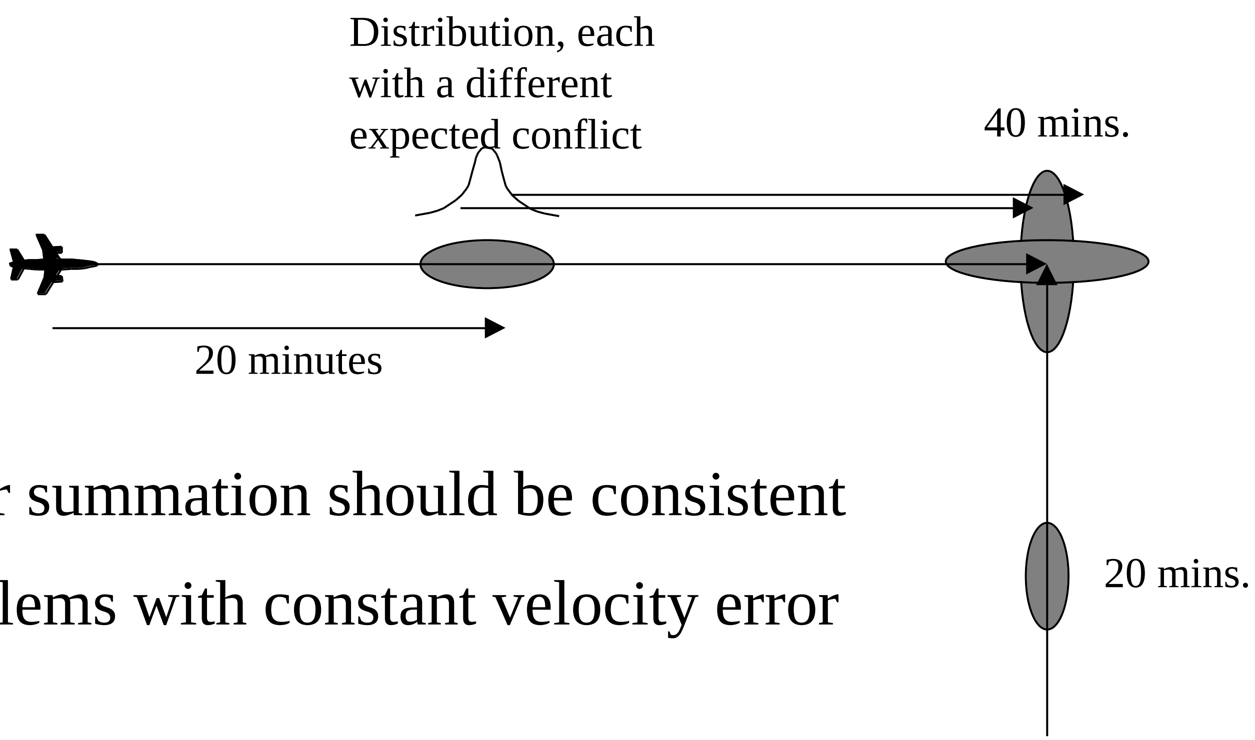
- Vector at t=0 imposed on 90°conflict case
- Maneuver decreases likelihood of encounter.
- Closer maneuvers require larger maneuvers





Tradeoff of Strategic versus Tactical Resolution

- Early resolution is lower cost, but has higher false alarms
- Analyze tradeoff of immediate resolution versus wait and see resolution



- Error summation should be consistent
- Problems with constant velocity error

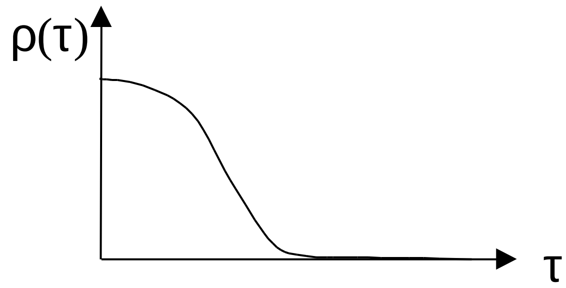
Seek Consistent Model of Wind Error

- Assume a generic auto-correlation function for along-track wind error (w) (e.g., stationary process, non-periodic error)

$$\rho(\tau) = E\left[w(t)w(t+\tau)\right]$$

$$= \frac{1}{\langle w^2 \rangle} \lim_{T \to \infty} \int_0^T w(t)w(t+\tau)\,d\tau$$

- For instance:



- Obviously, wind errors close in time are highly correlated, correlation decreases as they are separated in time

Positional Uncertainty - Limits

- Position uncertainty easily obtained through integration of wind uncertainty

$$x(T) = \int_0^T w(t)\,dt$$

- One can show, for small times:

$$\overline{x(T)^2} \approx 2\overline{w^2}\int_0^T (T-\tau)\,d\tau$$

$$\approx \overline{w^2}T^2$$

Linear RMS !

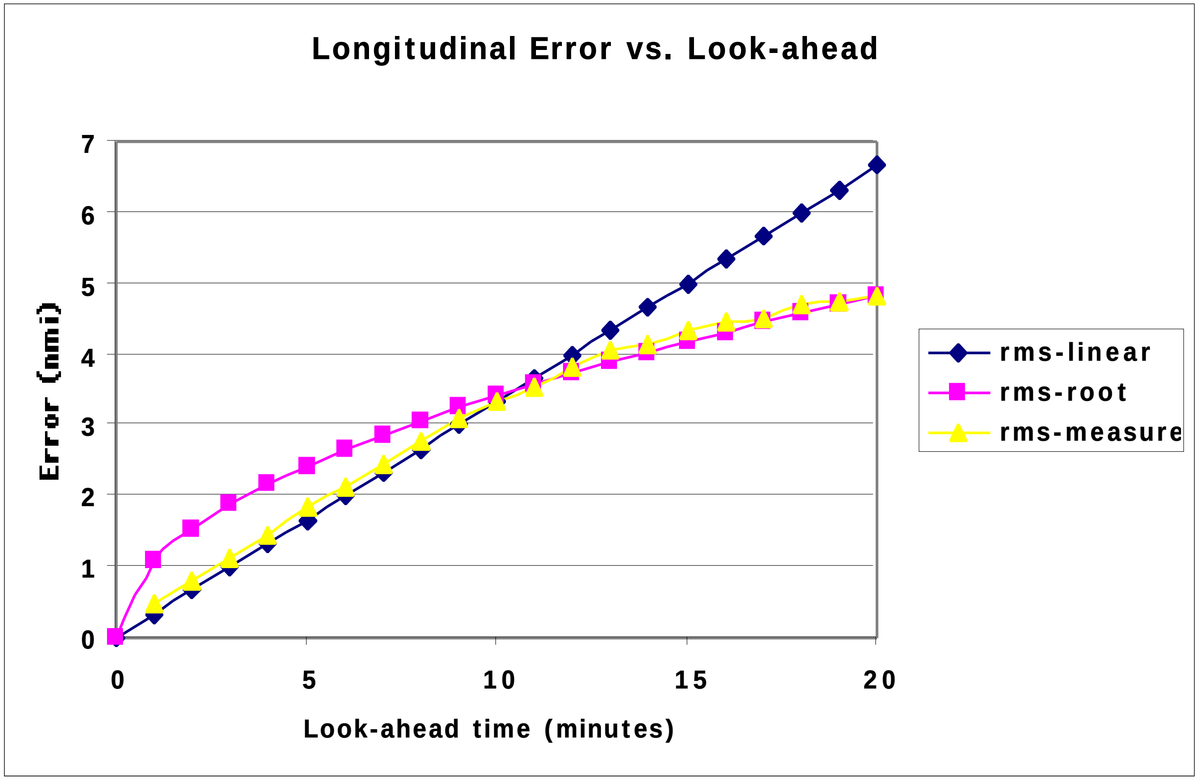
- And for large times:

$$\overline{x(T)^2} \approx 2\overline{w^2}T\int_0^\infty \rho(\tau)\,d\tau$$

$$\approx 2\overline{w^2}T(const.)$$

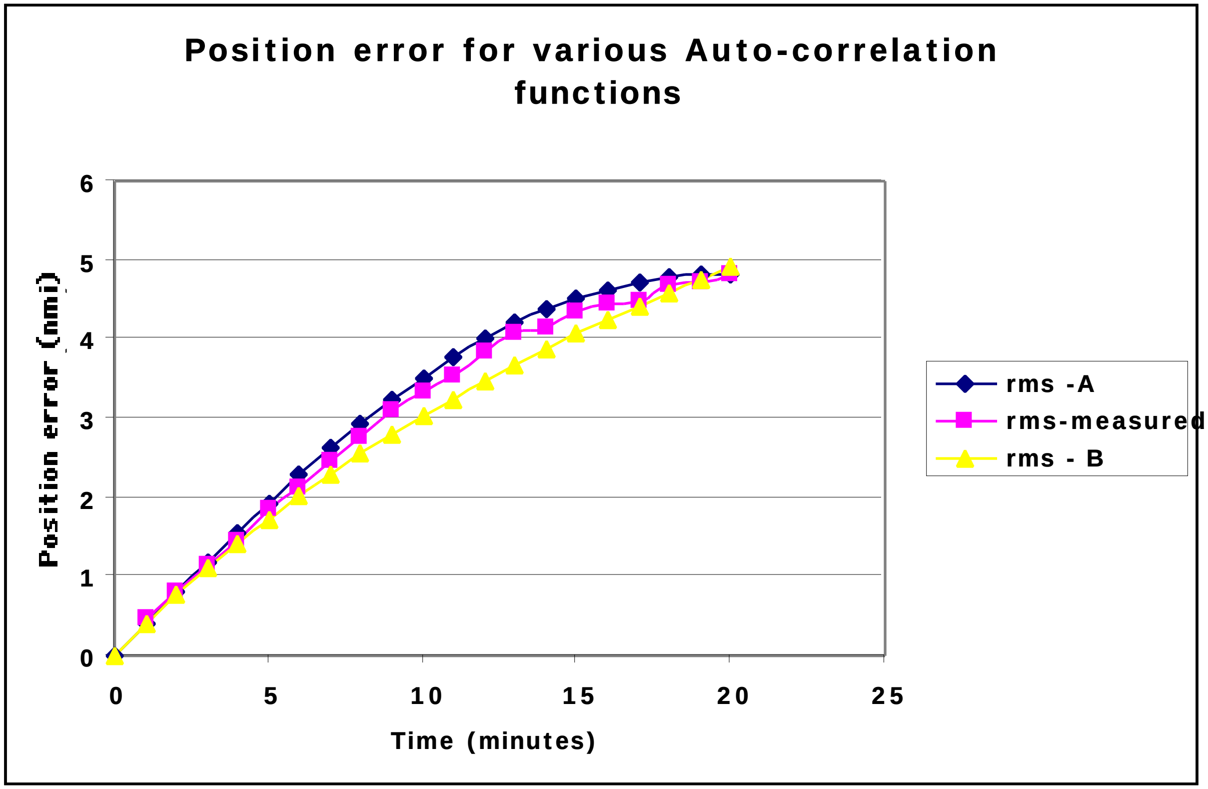
Square-root RMS

Positional Uncertainty Data



Extracted from: “Using Air-Ground Data Link to Improve Air Traffic Management Decision Support System Performance”, Wanke, C., 1st USA/Europe ATM Seminar, Saclay, 1997.

Example Auto-correlation Functions

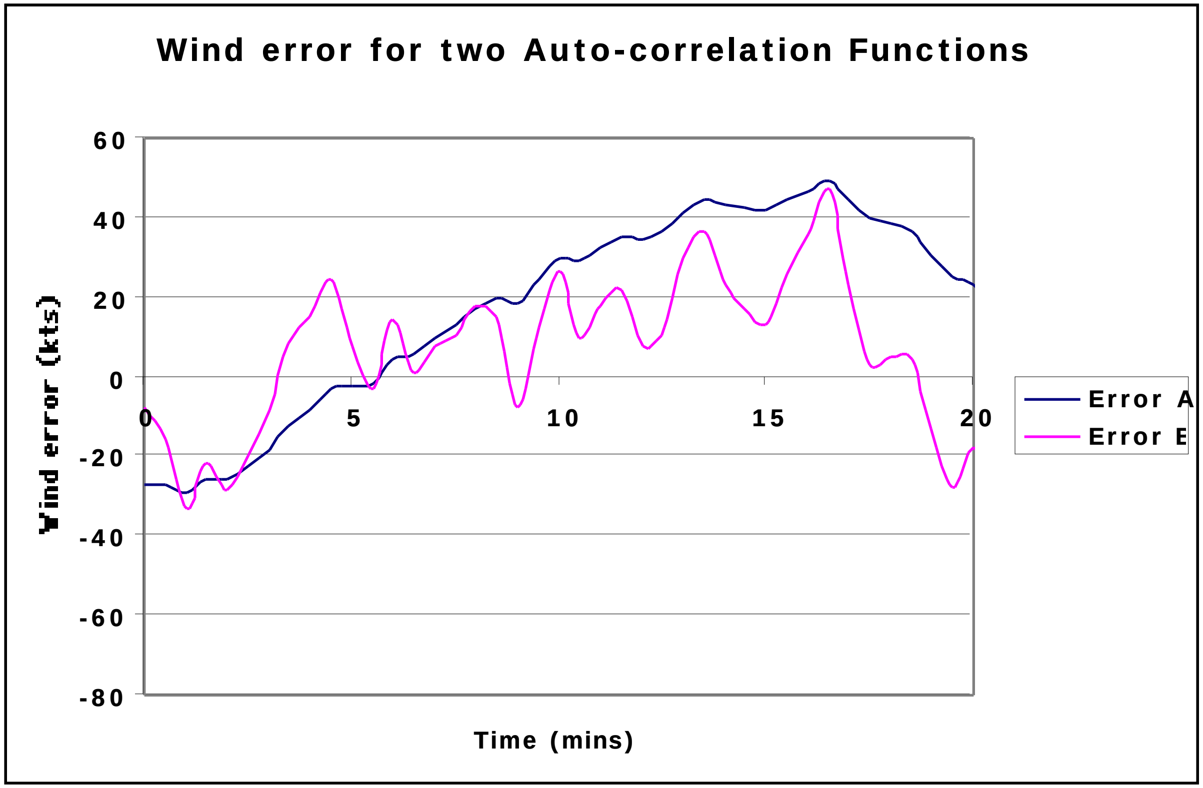


$$R_x(\tau) = \sigma^2 e^{-a|\tau|}\cos(b\tau)$$

$$R_x(\tau) = \sigma^2 e^{-\beta|\tau|}$$

Both have the same wind rms (σ) & close integrated position error, but noise signal can be radically different...

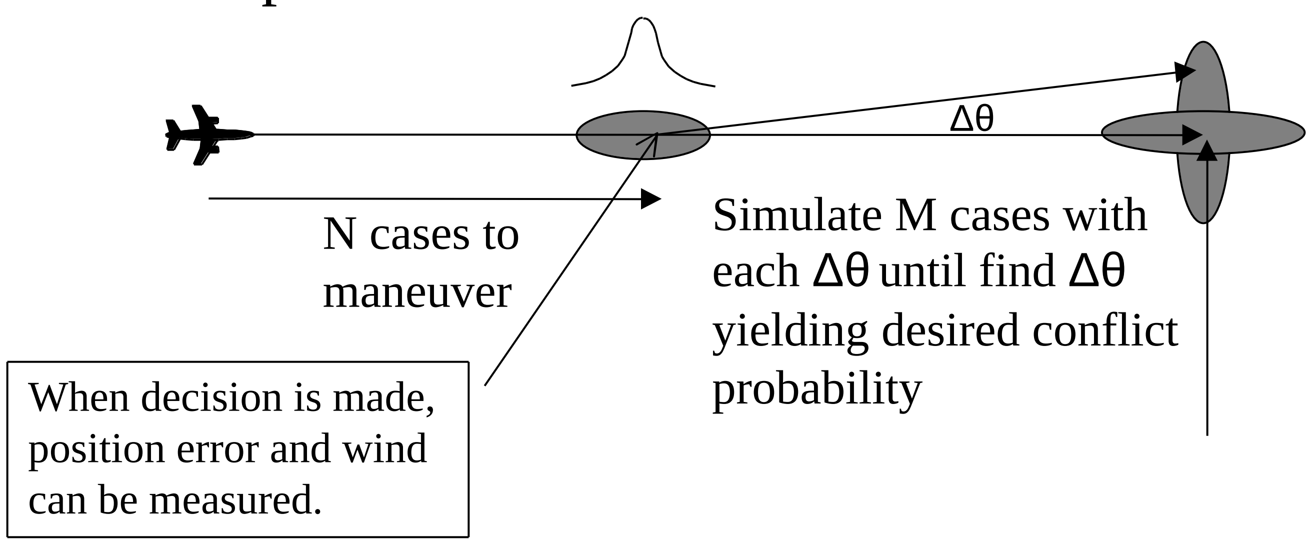
Resulting Error Signal



Typically reported quantities are identical, but radically different signals. Implications for conflict probability estimation.

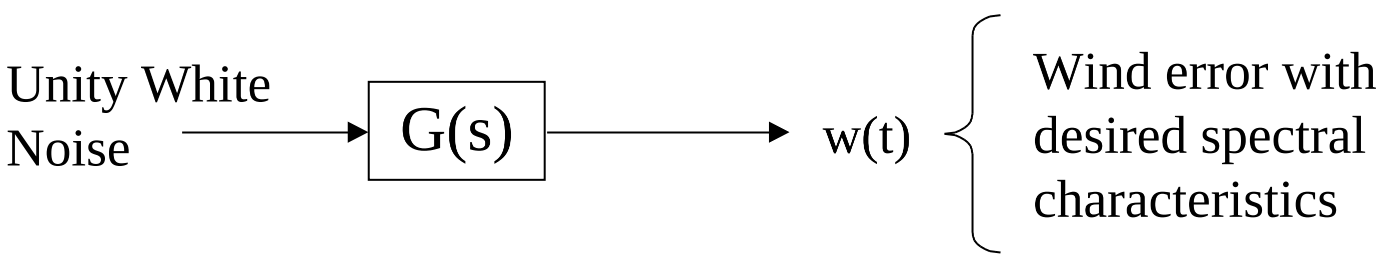
Monte-Carlo Simulation of Resolution Scenario

- Simulate simple conflict scenarios with different wind auto-correlation functions
- Compare strategic cost of resolution (early versus late)
- Simulate flight from t=0 to a maneuver, then obtain a vector that reduces the probability of conflict to an acceptable level
- Obtain expected value of maneuver at a future time

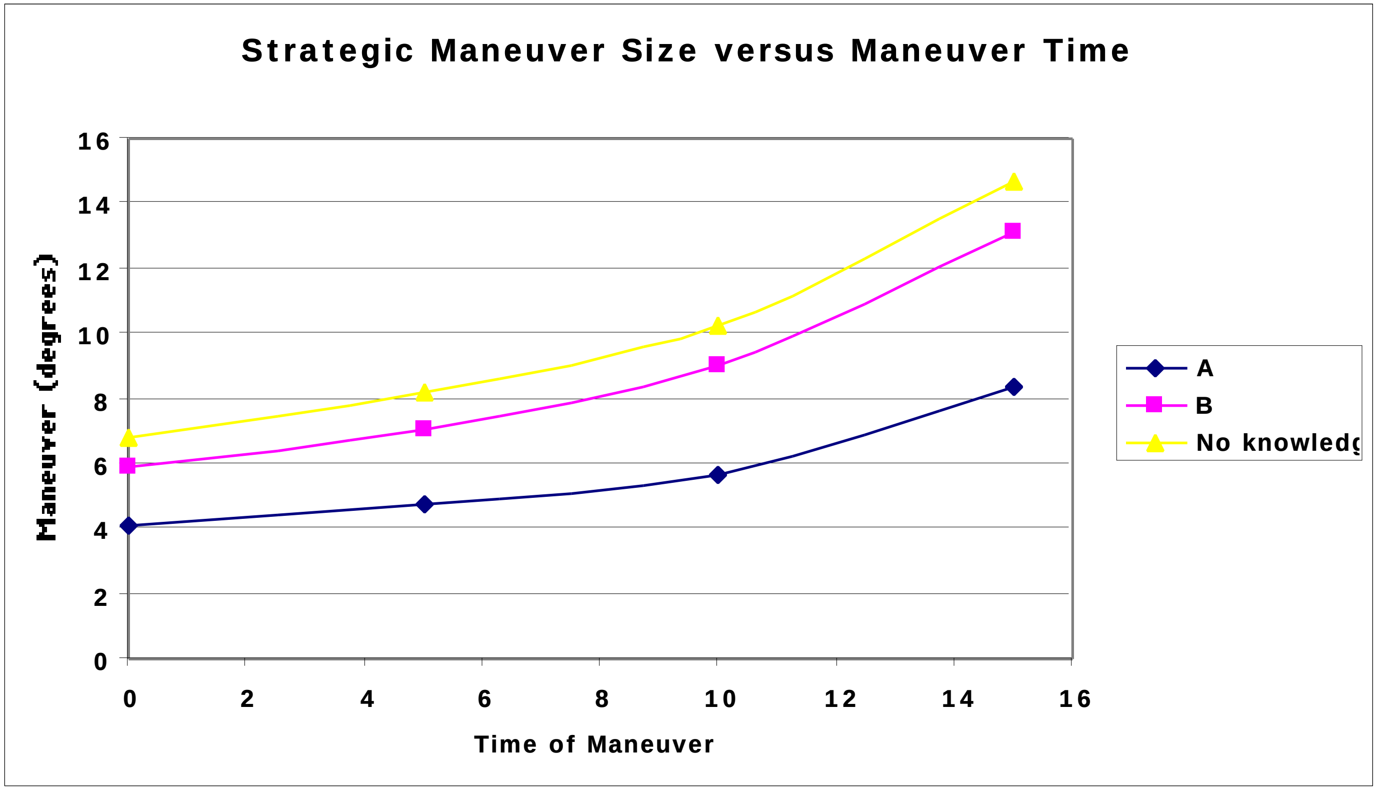


Use of Auto-correlation Function in Monte-Carlo Simulations

- Given wind auto-correlation function:
  - Obtain power spectral density function
  - Employ spectral factorization to obtain a minimum phase, rational transfer function for a shaping filter (G(s))



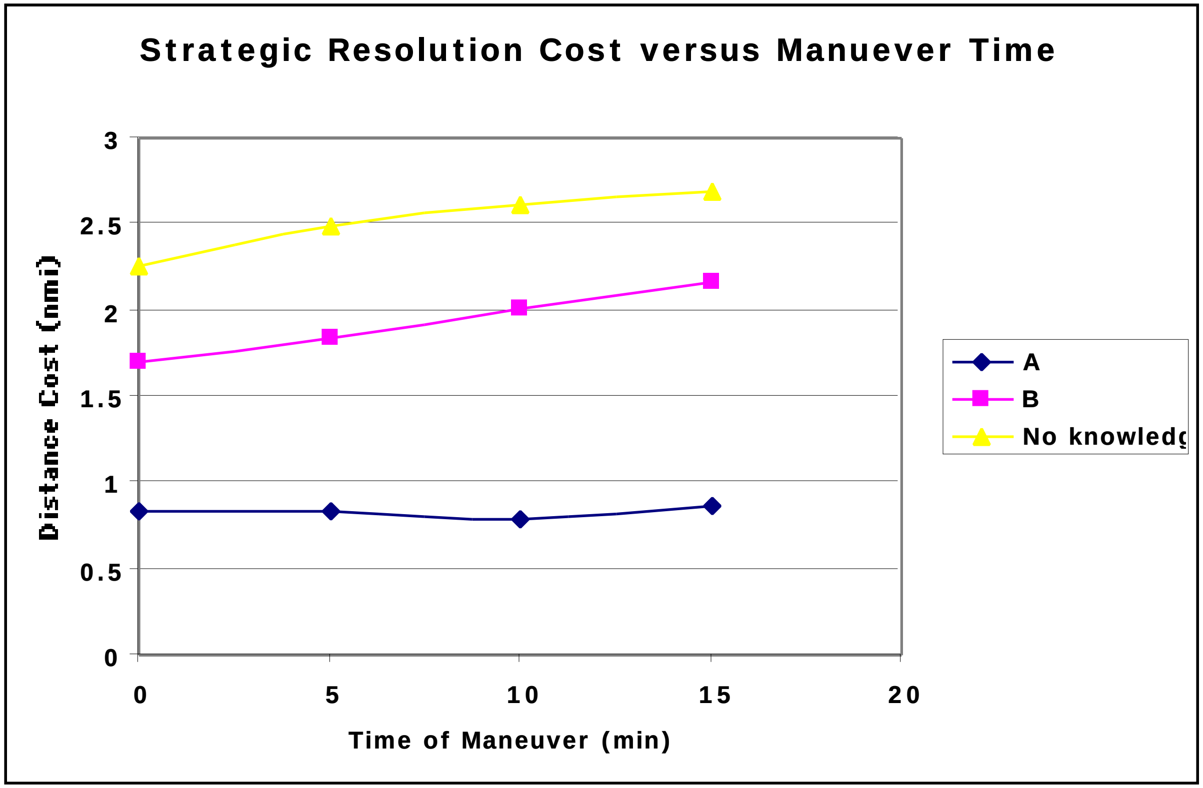
Strategic Resolution Maneuvers



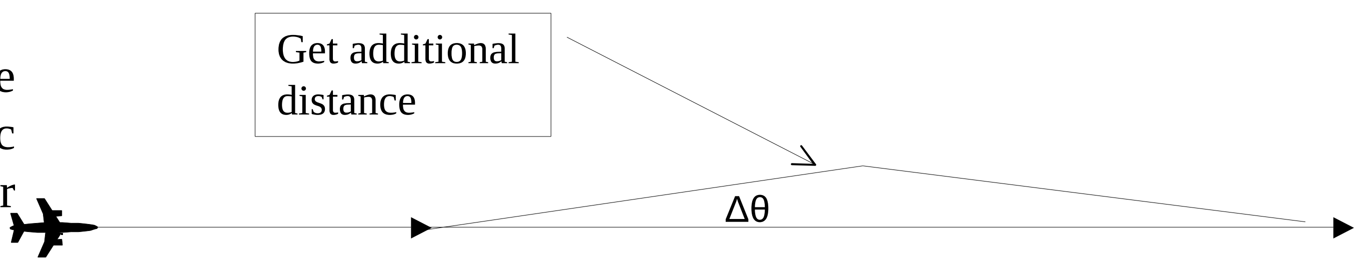
(Recall that A was the slowly varying signal)

Knowledge of measured wind and properties reduces strategic resolution cost. (More so if higher correlation.)

Cost of Maneuvers



Assume symmetric maneuver



Further Complications

- Assumption of *stationary* process may be incorrect, is it quasi-stationary?
  - From [7], we know that large wind errors can occur over certain regions and that these do persist
  - From [9], we know that turbulence (a high frequency component of the wind error) can be modeled as a non-stationary random process
- Discussion focused on along-track error, problem could be re-formulated as positional auto-correlation function to include multiple aircraft interactions
- Discrete errors such as the imprecise timing of gust fronts

Conclusions

- Validity of linear growth of positional uncertainty needs to be examined for longer time horizons
- Statistical properties of wind error affect conflict probe’s time horizon and derived benefits
  - Conventional measures of wind forecasting error such as RMS are insufficient to determine the performance of CD&R tools
- Obtaining an understanding of the statistical properties of the wind error will allow us to:
  - Credibly perform the strategic versus tactical conflict resolution tradeoff
  - Develop compensators for the wind errors, thereby improving conflict prediction

References

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